PREVENTION AND MITIGATION COUNTERMEASURES FOR NITIANGUO LANDSLIDES ON THE BASIS OF FIELD INVESTIGATION AND MODEL CALCULATION

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Abstract

Wenchuan earthquake of 12 May 2008 induced a vast majority of landslides, debris flows and other unfavorable geological bodies, which pose great risk to the property and physical security of local people. With the aim of reducing potential threat posed by secondary geological disasters, field investigation was conducted. Via field investigation we found that Nitianguo landslide is extremely unstable, and susceptible to slide under the influential of rainfall condition, human engineering activity or seismic activity. To ensure the accuracy and reliable of the field investigation, stability calculation model is employed in this research, which can facilitate the subsequent safety factor calculation. By means of model calculation, the following conclusions can be drawn: the safety factor of Nitianguo landslide is less than 1, which indicates that Nitianguo landslide is in unstable conditions, without engineering measures this landslide is prone to breakout. Combining the model calculation results with geological and topographical features of this area, the mitigation and prevention countermeasures can be proposed: Considering the property of the landslide itself, a cut slope is recommended as a prevention and mitigation measure. According to the location, scale, failure modes, stability and construction conditions, the proposed exploration area management should follow the principle of unified planning and prioritization.

Key words: counter-measures, landslide, prevention and mitigation, field investigation, model calculation

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1. Introduction

The term landslide denotes the movement of a mass of rock, debris or earth down a slope (Cruden, 1991) and may lead to large-scale natural hazards and contribute to a large fraction of long-term sediment yields from mountain areas (Dadson et al., 2004). Landslides are commonly observed in mountainous areas after intensive or long rainy periods, often leading to significant topographic changes. They constitute a potentially costly risk for human life and the built environment. A good understanding of landslide characteristics and mechanics is therefore of considerable geotechnical interest, particularly in the evaluation of potential mitigation strategies (Chen and Lee, 2003; Iverson, 1997; Johnson and Kehle, 1972; Takahashi and Takemura, 2005; Takahashi, 2007; Varnes, 1978). In the assessment of risk associated with landslide movement, the likelihood of slope failure is of prime interest. In terms of property development on slopes, the potential consequences of landslide debris invasion into the area of development are also of importance (Chen and Lee, 2003). To date, to better investigate and predict the landslide stability and mitigate the effect of hazards, a variety of both qualitative and quantitative approaches, including monitoring, measuring, model test, and numerical simulation, have been implemented (Jia et al., 2012; Jiao et al., 2011; Kaynia et al., 2008; Korup, 2005; Marcato et al., 2012; Song et al., 2009). Many uncertainties are often associated with the triggering and propagation of landslides, which greatly affected the accuracy of stability analysis of landslides. To better understand the formation mechanism of the landslides, and providing reliable property parameters for subsequent landslides stability analysis, this study analyzes the stability of the landslides on the basis of meticulously field investigation and model calculation, comprehensively combining the computational results with the regional geological features and rainfall characteristics put forward the countermeasures for disaster prevention and mitigation, with the aim of minimizing the socio-economic impact and landslide risk (Chen et al., 2006; Engel et al., 2011; Guo et al., 2016; Zhuang et al., 2010).

2. Study area

The Wenchuan earthquake of 12 May 2008 caused numerous co-seismic landslides (Cui et al., 2011). After earthquakes of this magnitude, most valleys and slopes are destabilized and conditions for debris flows and landslides are amplified. These hazards are typically very active during the following 10–20 years (Cui et al., 2009). As a consequence of the severe shocks, most valleys and slopes were destabilized and numerous geo-hazards, such as landslides, collapses, and unstable slopes, were triggered in the earthquake-affected area, which covered 50 badly affected counties and ten worst-affected counties in Sichuan province, SW China (Chen et al., 2009; Cui et al., 2011). Nitianguo landslide is one of the geo-hazards induced by Wenchuan earthquake (Fig. 1). The earthquake exacerbated the deformation of Nitianguo landslide and greatly reduced its stability, which can lead to its instability under the effect of rainfall, earthquake, or human activity. In addition, Nitianguo landslide posed great threat to the people living downstream (usually about 158 people) and threatened two transmission towers and about 500m of highway. The potential economic cost of this landslide is around 7.36 million RMB (renminbi). With the aim of reducing the property loss and casualties, analyzing the stability of this landslide is necessary and meaningful. In this
research, rigorous field investigation was conducted first, which can help us acquiring the detailed data of the area where the landslide situated in. Then relevant calculation model is employed, which can greatly facilitate the subsequent stability analysis process, combined the model computational results with the field investigation, the stability condition of the Nitianguo landslide can be analyzed reasonably. On the basis of the analysis, the countermeasures for prevention and mitigation can be proposed.

Fig.1 The general situation of Nitianguo landslide

3. Methodologies (field investigation and model calculation)

In this paper, two basic approaches (field investigation and model calculation) are employed to explore the stability of Nitianguo landslide. The field investigation can help us acquire the data that closely related to the landslide, which can be useful and can greatly facilitate the subsequent model calculation process. Based on the fundamental data of the study area and the results of model calculation, a comprehensive stability analysis of Nitianguo landslide can be performed. By analysis of the safety factor of Nitianguo landslide, the stability of Nitianguo landslide can be identified, and the prevention and mitigation countermeasures can be proposed, which can greatly reduce the risk posed by Nitianguo landslide.

3.1 Field investigation

With the help of Wolong Reserve Management Bureau, Wolong Land Resources Bureau, and Wolong township government, field investigation was conducted and lasted for around one month. The scope of the investigation not only concentrated on the landslide itself but also included the adjacent zone (within a 20metre radius) and the area susceptible to Nitianguo landslide. Through the field investigation, the fundamental data of the study area is identified, which are described in the following sections.

Climatically, the study area falls into the subtropical humid climate zone; during winter the area is significantly affected by the Qinghai-Tibet Plateau climate, while in summer it is mainly dominated by the southwest and southeast monsoon climate. The mean annual precipitation is 930.2mm, and the rainfall is mainly concentrated during the period from May to September, which contributes more than 78% of the total precipitation throughout the year. According to the rainfall contour diagram of Sichuan province illustrated in the manual of flood calculations for small and medium-sized basins, the rainfall data for 10 minutes and 1, 6, and 24 hours can be acquired and the corresponding amounts are 10, 20, 65, and 120mm, respectively.
By means of field investigation, the lithology, seismic activity, and tectonic movements of the study area can be determined and consist of the following: exposed strata mainly concentrated in the Quaternary alluvial layer (Q₄ₐl+ₚl), the eluvial layer (Q₄ₐl+dl), colluvium (Q₄col), and the landslide deposition layer (Q₄del). Moreover, the bedrock in the study area is fragmentized due to the effect of tectonic movement and weathering, which can greatly facilitate landslide movement in subsequent rainfall conditions.

The study area is located in Huaxia tectonic belt, which belongs to Longmenshan tectonic system, and the tectonic movement is extremely complex. Due to the effect of strong tectonic movements, the bedrock becomes loose and can thus provide favourable conditions for the development of collapse, landslides, and other geological disasters.

### 3.2 Model calculation

Since most landslides and other deformable bodies mainly constitutes of soil, the deformation of the slope is governed by the weak interface with maximum shear stress. Therefore, we can use the transfer coefficient method to compute the safety factors of the slopes. Following this method, the soil is initially divided vertically into several strips (Fig. 2) and each strip is taken as a rigid body while taking the interaction forces between the strips into consideration at the same time. On the basis of the above description, we assumed that the residual sliding force was parallel to the sliding surface, and then the driving moment and the resisting moment exerted on individual strips can be calculated, as shown by the stress analysis diagram in Fig.2.

![Fig. 2 Calculation model of transfer coefficient](image)

(1) The computational formula for computing the safety factor is expressed as follows:

\[
K_j = \frac{\sum_{i=1}^{n-1} (W_i(1-r_i)\cos \theta_i)g_{\theta_i} + C_i L_i \prod_{j=1}^{n-1} \psi_j) + R_n}{\sum_{i=1}^{n-1} (W_i(\sin \theta_i + A \cos \theta_i) \prod_{j=1}^{n-1} \psi_j) + T_n} \quad (1)
\]
\[
R_i = (W_i((1 - r_i)\cos \theta_i - A\sin \theta_i) - R_{Di})s_i \phi_i + C_iL_i
\]  
(2)

\[
T_i = W_i(\sin \theta_i + A\cos \theta_i) + T_{Di}
\]  
(3)

\[
\prod_{j=i}^{n-1} \psi_j = \psi_i \psi_{i+1} \cdots \psi_{n-1}
\]  
(4)

\(\psi_i\) is the residual sliding force transferred from strip \(i\) to strip \(i+1\) (\(j = i\)); that is:
\[
\psi_i = \cos(\theta_i - \theta_{i+1}) - \sin(\theta_i - \theta_{i+1})\tan \phi_{i+1}
\]  
(5)

where \(W_i\) is the weight of the \(i\)-th strip; \(T_i\) is the sliding force of the \(i\)-th strip; \(R_i\) is the resistance force of the \(i\)-th strip; \(\theta_i\) is the inclination of the sliding surface of the \(i\)-th strip; \(\beta_i\) is the angle between the sliding surface and the ground water (here, ground water denotes the water level below the \(i\)-th strip); \(C_i\) is the cohesion forces of the \(i\)-th strip; \(\phi_i\) is the internal friction angle of the \(i\)-th strip; \(A\) is the coefficient of earthquake acceleration in the area where the seismic fortification grade is level 6, \(A\) is equal to 0.05; \(R_{Di}\) is the component of seepage force perpendicular to the sliding surface, and \(R_{Di}\) is equal to \(N_{wi}\tan \beta_i \sin(\alpha_i - \beta_i)\); \(T_{Di}\) is the component of seepage force parallel to the sliding surface, and \(T_{Di}\) is equal to \(N_{wi}\tan \beta_i \cos(\alpha_i - \beta_i)\); \(N_{wi}\) is pore water pressure, and \(N_{wi}\) is equal to \(\gamma_w h_{i+1} L_i\); \(r_U\) is the ratio of pore pressure, and
\[
r_U = \frac{v_w \times \gamma_w}{v_s \times \gamma_s} \approx \frac{s_u}{s_t \times 2},
\]
where \(v_w\) is the volume of the strip below water level, \(v_s\) is the total volume of the strip, \(s_u\) is the area of the strip below the water level, \(s_t\) is the total area of the strip, and \(\gamma_w\) and \(\gamma_s\) represent the unit weight of the water and strip (sliding body), respectively.

(2) The computational formula for computing the residual sliding force expresses as follows:
\[
P_i = P_{i-1} \psi_{i-1} + K_s \times T_i - R_i
\]  
(6)

where \(P_i\) is the sliding thrust of the \(i\)-th strip (kN/m); \(P_{i-1}\) is the residual sliding force of \(i\)-th strip (kN/m); and \(K_s\) is the designed safety factor, with a value of 1.15 here.

Through field investigation, the influential factors of the landslide were studied meticulously. By analysis we found that Nitianguo landslide is mainly affected by its own weight, rainfall, and seismic activity. Based on these influential factors, we determined the load conditions and computed the safety factors under different load conditions. The load conditions were mainly grouped into three types: condition 1 represents the effect of own weight of landslide, condition 2 represents the combined effect of own weight of landslide and rainfall conditions(34mm/h), and condition 3 represents the effect under own weight of landslide, rainfall conditions(34mm/h), and seismic activity.

4. Results of model calculation

On the basis of the model describes in section 3.2, the calculation is conducted and the calculation results can be obtained. Then the safety factors of each strip is identified, by comparison we found the minimal and maximum safety factor of the strips under condition 2 (landslide bodies) are 0.9 and 0.96 respectively. Therefore, we concluded that Nitianguo landslide is under unstable conditions, in the following years, under the influential of
rainfall, seismic activity and human engineering activity, Nitianguo landslide poses great risk to local economic development and human security

**Table 1 Model calculation results**

(Here conditions 1, 2 and 3 represents the effect under own weight of landslide, the effect under own weight of landslide and rainfall (34 mm/h), the effect under own weight of landslide, rainfall (34mm/h) and seismic activity, respectively)

<table>
<thead>
<tr>
<th>Load conditions</th>
<th>Condition 1</th>
<th>Condition 2</th>
<th>Condition 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Safety factor</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Strips Minimal</td>
<td>1.02</td>
<td>0.9</td>
<td>0.61</td>
</tr>
<tr>
<td>Maximum</td>
<td>1.13</td>
<td>0.96</td>
<td>0.66</td>
</tr>
</tbody>
</table>

According to "Landslide Prevention Engineering Design and Construction of Calculation Specification", on the basis of the classification of landslide stability(Table 2), the stability state under different stability factors can be determined.

**Table 2 Classification of landslide stability (Kst is the designed safety factor)**

<table>
<thead>
<tr>
<th>Stability factor of the landslide</th>
<th>( K_s &lt; 1.00 )</th>
<th>( 1.00 &lt; K_s \leq 1.05 )</th>
<th>( 1.05 &lt; K_s \leq K_{st} )</th>
<th>( K_s \geq K_{st} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stability status</td>
<td>Unstable</td>
<td>Less stable</td>
<td>Basically stable</td>
<td>Stable</td>
</tr>
</tbody>
</table>

Referred to Table 2 we can conclude that Nitianguo landslide is in unstable state, without engineering measures this landslide will probably causes great risk to local economic development.

5. **Countermeasures and discussions**

On the basis of field investigation and model calculation results, the stability of Nitianguo landslide is identified: Nitianguo landslide was in unstable state, without engineering measures, this landslide probably causes heavy human casualties and economic losses. With the aim of reducing the disaster posed by this landslide, combining the geological feature of this area, mitigation and prevention can be proposed, thus in turn can greatly reduce the risk. According to the location, scale, failure modes, stability and construction conditions, the proposed exploration area management should follow the principle of unified planning and prioritization.

By means of field investigation, we found that the slide body is very thin, while the slope of the landslide is greater, combining with the results of model calculation, we propose that cutting slopes is the reasonable way to improve the stability of this landslide. In addition, there are some unfavorable geological bodies close to this landslide, and this unfavorable geological body will have potential effect on Nitianguo landslide. Therefore, some engineering measures required to be adopted simultaneously, and the engineering measures mainly follows into three types: active or passive protection network for rock collapse, retaining wall and passive network for slippery bodies, and cutting slopes for Nitianguo landslide. Moreover, the monitoring system needed to be established in this area to detect and analyze the displacement and deformation of the landslide and other unfavorable bodies.
6. Conclusions
By means of field investigation and model calculation, the following conclusions can be drawn: The stability of the landslide was mainly affected by the 12 May 2008 Wenchuan Earthquake and subsequent rainfall infiltration. Continuous heavy rainfall plays a crucial role in landslide stability analysis. In addition, human activity and weathering have also influenced the stability of Nitianguo landslide.

Under natural conditions, this landslide is in unstable state. Considering the property of the landslide itself, cutting slope is recommended as a prevention and mitigation measure. According to the location, scale, failure modes, stability and construction conditions, the proposed exploration area management should follow the principle of unified planning and prioritization.

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